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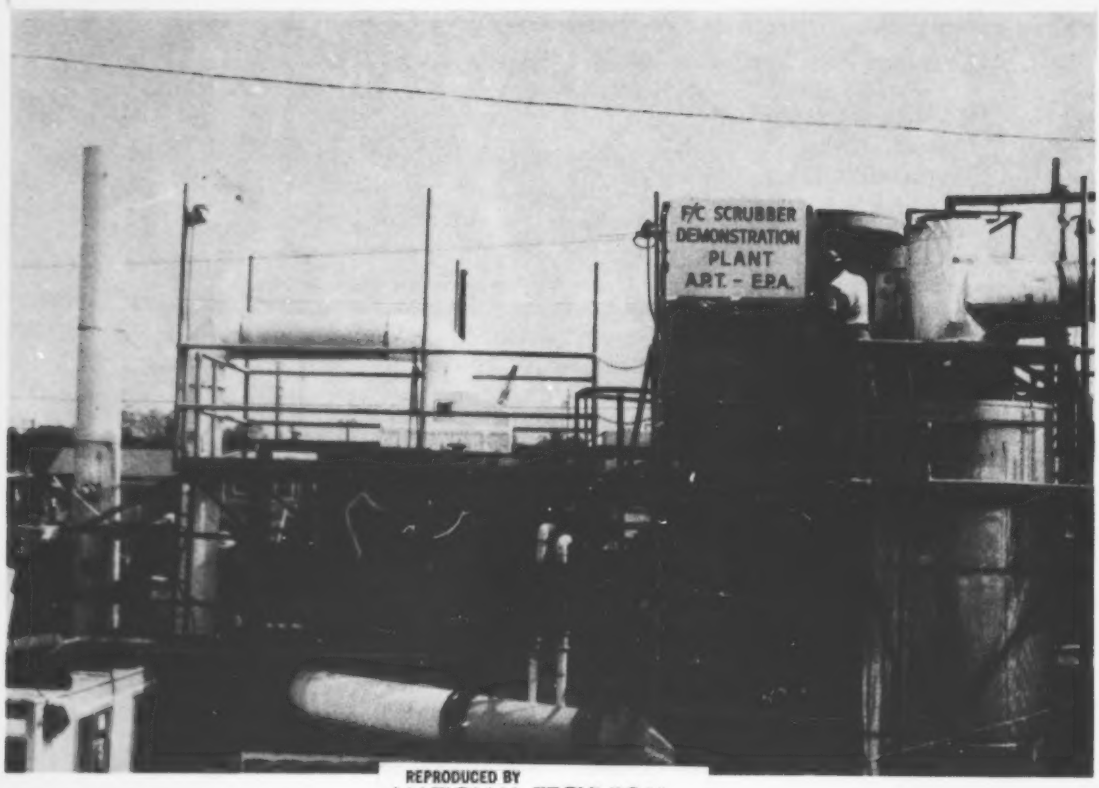

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ABSTRACT

Flux force/condensation (F/C) scrubbing involves the use of water vapor condensation effects to enhance fine particle collection. F/C scrubbing offers significant cost advantages over conventional control equipment for a large number of industrial sources. Generally it is attractive when high removal efficiencies are required for fine particles; and the flue gas enthalpy is sufficiently high or spent steam is available.

The EPA fine particle scrubber program has been instrumental in identifying, understanding, and quantifying flux force and condensation effects in wet scrubbers. EPA also has taken a leading role in developing and demonstrating F/C scrubbers for industrial applications.

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ABBREVIATIONS AND SYMBOLS

CFM - cubic feet per minute

DNm^3/min - dry normal m^3/min (at 1 atm, 20°C)

F/C - flux force and condensation

n_p - particle number concentration, cm^{-3}

psig - pounds per square inch gage

μmA - aerodynamic micrometers, $\mu m \sqrt{g/cm^3}$

ρ_G - air density, g/cm^3

ρ_p - particle density, g/cm^3

FLUX FORCE/CONDENSATION WET SCRUBBING

INTRODUCTION

In 1970, the EPA fine particle scrubber program was initiated with the Wet Scrubber Systems Study. The principal result was the publication of the Scrubber Handbook (Calvert, et al., 1972), reviewing the state-of-the-art and pointing out several paths which might lead to improvements in scrubber technology. Since 1972, the broad objective of the EPA program has been to develop and demonstrate low pressure drop (30-50 cm water column) scrubber systems capable of collecting at least 90% by mass of particles smaller than 3 μm in diameter.

A major drawback with conventional wet scrubbers is the large energy expenditure required to achieve high removal efficiencies for particle diameters smaller than 2 to 3 μm. Primarily this is a result of the decreased effectiveness of inertial mechanisms for separating very small particles from a gas stream.

The Wet Scrubber Systems Study recommended investigating phenomena which can exert forces other than inertial forces on particles and where warranted, developing equipment to use these forces for particle collection. Along this line, a major thrust has been aimed at developing and demonstrating flux force/condensation (F/C) scrubbers.

F/C SCRUBBER DEVELOPMENT

Essentially an F/C scrubber is any wet scrubber which is designed to take advantage of water vapor condensation effects to enhance particle collection. A simplified F/C scrubber system is illustrated schematically in Figure 1. Some of the water vapor condenses on the particles causing their mass and diameter to increase and thereby making them easier to collect. The rest of

the condensing vapor sweeps particles with it as it moves toward the cold surface and condenses. To a lesser extent particle collection is also enhanced by thermal forces resulting from the temperature gradient between the gas and the cold surface. The diffusion and thermal forces are termed "flux" forces.

Investigators had realized for years that anomalously high collection efficiencies could be obtained at relatively low pressure drops when water vapor condensation occurred ahead of the scrubber. However, no systematic investigation had been conducted which could be used to design and optimize scrubbers to take advantage of flux force and condensation effects. Since 1972 the EPA has taken a leading role in this area, developing F/C scrubbing through theoretical, laboratory, pilot plant and full scale industrial demonstration plant projects.

Early Development

The feasibility of F/C scrubbing for fine particulate control was investigated and reported by Calvert, et al. (1973) and Calvert and Jhaveri (1974). The work involved extensive theoretical studies and exploratory experiments on a bench scale. Preliminary engineering and cost analyses were conducted and it was recommended that pilot scale F/C scrubbers be built and tested.

Two pilot scale F/C scrubbers were built to handle from 14 to 28 m^3/min (500-1,000 CFM) actual gas flow rate. Based on the results of the bench scale work, multiple sieve plate and horizontal spray scrubber configurations were selected for the pilot study. The results were very promising both from a technological and from an economic point of view. Depending on the process characteristics, the operating costs for an F/C scrubber were predicted to be as low as 1/3 or less of the operating cost for an equivalent high energy scrubber. Details of the pilot plant studies were reported by Calvert, et al. (1975) and Calvert and Yung (1976).

Demonstration Plants

EPA has funded two full-scale industrial F/C scrubber demonstration plants. The first demonstration plant was a multiplate F/C scrubber used to control fine particle emissions from a secondary metal recovery furnace. Control of the entire source effluent (200 m^3/min or 7,000 ACFM) at temperatures up to 800°C required both particle collection and acid gas absorption. The demonstration plant performance was consistent with the earlier bench-scale and pilot-scale studies.

The system was generally capable of about 90% to 95% efficiency on particles with a mass median aerodynamic diameter of 0.7 to 0.8 μmA (about 0.3 μm physical diameter for particles with a density of 4.0 g/cm^3). This efficiency was achieved with a 68 cm (27 in) W.C. gas phase pressure drop. A conventional high energy scrubber without F/C effects would have required pressure drops of roughly 250 cm (98 in) W.C. for 90% and 535 cm (210 in) W.C. for 95% particle collection efficiency.

Detailed results and economic analyses for the demonstration plant have been reported by Calvert, et al. (1977) and Calvert and Gandhi (1977).

The second F/C scrubber demonstration currently is underway. A gas-atomized spray F/C scrubber will be used to control fine particle emissions from a gray iron foundry cupola. Plant startup is scheduled for late fall, 1978.

DESIGN CONSIDERATIONS

One of the major goals of the EPA F/C scrubbing development program has been to quantify the important F/C effects by identifying key process parameters and developing useful engineering models for design and performance prediction purposes. This goal has been achieved through the systematic development and demonstration program described above, resulting in a simplified and improved design method for F/C scrubbing as reported by Calvert and Gandhi (1977). The most important parameters and design concepts are discussed briefly on the following pages.

Particle Size Distribution

One of the most important design parameters for any particulate control device is the particle size distribution. In an F/C scrubber there are two size distributions which must be considered. The initial size distribution is that leaving the source and entering the saturator and condenser. This size distribution is used to predict the collection efficiency in the saturator and initial stages of the condenser before condensation occurs. It also is important in determining the final size distribution after condensation.

The final or "grown" particle size distribution is that which results from water vapor condensation on the particles. Typical initial and grown particle size distribution curves are shown in Figure 2. A convenient design assumption is that each particle receives the same mass of condensing vapor, independent of the particle diameter. This explains the observation that small particles grow much more than large particles. Although this assumption is not strictly valid, it agrees well with experimental observation for particle diameters of interest (larger than about 0.1 μm).

Particle Number Concentration

Because all particles receive an approximately equal mass of condensate, the number concentration of particles is very important in determining the final grown particle size. Particle number concentration is not generally an important parameter for other particulate control techniques and therefore it often is difficult to find adequate data. However, these data are essential for proper design of F/C scrubbing systems. Representative number concentrations for industrial sources can range from about 10^7 to 10^9 particles/DNcm^3.

Particle Condensation Ratio

Most of the water vapor will condense on the cold, solid or liquid surfaces of the condenser. Only a fraction of the vapor will condense on the particles. This fraction is called the

particle condensation ratio. It is affected by many parameters including: inlet gas temperature, bulk liquid temperature, particle number concentration, particle diameter, liquid phase heat transfer coefficient, and condenser geometry. Particle condensation ratios ranging from 15% to 40% have been predicted for several combinations of parameters in a sieve plate condenser. For a combination of parameters such as might be encountered in a practical situation a value of 0.25 appears to be reasonable for a plate type condenser. This is equivalent to saying that 25% of the condensing vapor goes to the particles and 75% goes to the cold surfaces.

Particle Properties

In the design model, particles are assumed to be wettable, but insoluble. If the emitted particles were soluble in water, the expected performance for the system would be better. The solubility of the particles in water would depress the vapor pressure at the particle-gas interface, resulting in nucleation at a lower saturation ratio and more growth at a given saturation ratio.

Particle density also is important. This usually is accounted for by using the particle aerodynamic diameter for all particle collection calculations. The difference in particle and liquid densities must be considered when predicting grown aerodynamic diameters.

Contribution of Flux Forces

Particle collection by thermal gradient forces (thermophoresis) is only of minor importance and usually is neglected when predicting the performance of an F/C scrubber.

Diffusion flux forces (diffusiophoresis) however, are significant and must be considered. Detailed mathematical models exist for predicting diffusiophoretic deposition velocities and particle collection efficiencies. These models are complicated and cumbersome to use, requiring a step-by-step numerical integration over the period of condensation.

Whitmore (1976) discovered that the fraction of particles removed by diffusion of the condensing vapor is approximately equal to the fraction of the gas which condenses. In other words, if some fraction of the gas is transferred to the liquid phase it

will carry along its load of suspended particles. It turns out that this simplifying assumption is extremely useful for design purposes if modified to account for the molecular weight gradient and the fraction of condensate which condenses on particles.

PRACTICAL APPLICATIONS

In general, F/C scrubbing is attractive economically when high removal efficiencies are required for fine particle emissions; and the flue gas enthalpy is higher than 100 kcal/kg or spent steam is available in the plant. These conditions are common for industrial combustion processes, which include several major stationary pollution sources in the United States. Table 1 lists some of the major industrial particulate pollutant sources for which F/C scrubbing is attractive. It is clear that F/C scrubbing is a feasible and attractive particulate control method for several major industrial sources.

General Features

Although the details of F/C scrubbing system designs will be different for each source, the overall process designs will be similar to that shown in Figure 3. Some general economic features of F/C scrubbing are discussed below.

Experimental pilot plant results indicate that it should require from 0.1 to about 0.3 g water vapor condensed/g dry gas in a F/C scrubber to attain high collection efficiency for fine particles. Such a condensation ratio generally requires preconditioning of the scrubber inlet gas to increase its moisture content.

Gas preconditioning could be done either by direct introduction of spent steam if the gas is dry and has low enthalpy, or by evaporation of sprayed water when enough enthalpy is available in the gas. Direct injection of steam is beneficial because it can increase the local saturation ratio appreciably higher than 1.0, which is necessary to initiate the growth of hydrophobic particles.

Cooling water is needed to condense the desired amount of vapor in the scrubber. In an industrial system the water is

cooled in an evaporative cooling tower using ambient air, and then recirculated to the F/C scrubber. In cooling towers of conventional design, the change in water temperature is kept below about 17°C (30°F). A larger water temperature differential can be achieved in cooling towers of special design but the costs will be higher than usual, and there may be undesirable features such as fog formation. If the water temperature increase in the scrubber is 17°C (30°F), about 32 g of cooling water will be required to condense 1 g of water vapor.

Steam Introduction

While the performance of an F/C scrubber at a given condensation ratio is better if part or all of the water vapor is introduced as steam (i.e, 100% H_2O), the cost of purchased steam will generally be prohibitively high. However, under the right circumstances the use of some steam introduction could be economical.

The steam required for injection could be low pressure, less than 2 atm gage (30 psig) spent steam. It may be obtained from the feed line to the boiler condenser in a process plant or generated in a low pressure waste boiler in a metallurgical operation. In this case, the steam cost would be significantly lower and will depend on the specific manufacturing process.

Figure 4 shows the predicted penetration for an F/C venturi scrubber as a function of condensation ratio and gas phase pressure drop. These predictions are conservative in that they assumed the initial particle nuclei had negligible mass and diameter. The amount of steam required to achieve a given penetration at a specified pressure drop is equivalent to "q'". The economics of steam generation will depend on the required penetration and the savings in power usage associated with the lower pressure drop required for F/C scrubbers.

In general, a F/C scrubber using some purchased steam would have lower operating costs compared to a venturi scrubber. Also, the most important mechanisms in F/C scrubbing (diffusiophoresis and particle growth by condensation) are practically insensitive to particle size. Thus, F/C scrubbing would become economically

more attractive as the size of the particles to be controlled becomes smaller.

Economic Feasibility

The economic feasibility of an F/C scrubber system used to control emissions from a gray-iron foundry cupola was reported by Calvert, et al. (1975). A comparison between the estimated costs of the F/C scrubber system and a conventional high energy scrubber system are presented in Table 2. Both capital and operating costs are cheaper with the F/C scrubber system. The largest difference is in the power costs where the lower pressure drop required for F/C scrubbing results in substantial savings.

Based on the results of the first demonstration plant, an optimum design for an F/C scrubber was obtained for controlling emissions from a premium wire recovery furnace. The costs are compared with a conventional high energy scrubber in Table 3.

CONCLUSIONS

The EPA fine particle scrubber program has been instrumental in identifying, understanding, and quantifying flux force and condensation effects in wet scrubbers. As a result, it is now possible to use a proven engineering design model to design F/C scrubbers for new sources, or to modify existing scrubbers to take better advantage of F/C effects.

EPA has demonstrated on laboratory, pilot and industrial scales, that F/C scrubbing is technologically feasible and attractive. Furthermore, F/C scrubbing offers very significant cost savings over conventional control equipment for a large number of industrial sources. EPA involvement in F/C scrubbing is continuing with further industrial demonstration projects.

TABLE 1. MAJOR INDUSTRIAL PARTICULATE SOURCES FOR WHICH F/C SCRUBBING IS ATTRACTIVE

INDUSTRY	SOURCE
Iron & Steel	Sinter Plants Coke Manufacture Blast Furnaces Steel Furnaces Scarfing
Forest Products	Wigwam Burners Pulp Mills
Lime	Rotary Kilns Vertical Kilns
Primary Nonferrous	
Aluminum	Calcining Reduction Cells
Copper	Roasting Reverberatory Furnaces Converters
Zinc	Roasting Sintering Distillation
Lead	Sintering Blast Furances Dross Reverberatory Furances
Asphalt	Paving Materials Roofing Materials
Ferroalloys	Blast Furnaces Electric Furnaces
Iron Foundry	Furnaces
Secondary Nonferrous Metals	
Copper	Material Preparation Smelting and Refining
Aluminum	Sweating Furnaces Refining Furnaces Chlorine Fluxing
Lead	Pot Furnaces Blast Furnaces Reverberatory Furances
Zinc	Sweating Furnaces Distillation Furnaces

TABLE 2. COST COMPARISON OF CUPOLA EMISSION CONTROL SYSTEMS

COST ITEMS	HIGH ENERGY SCRUBBER SYSTEM ($) (1)	F/C SCRUBBER SYSTEM ($)
A. Capital Costs		
1. F.O.B. quencher with internals, flange to flange.	(4)	16,050
2. F.O.B. scrubber with internals, flange to flange including entrainment separator	24,590	42,910
3. F.O.B. cooling tower	--	46,200
4. Fans, motors and motor starter	206,690	46,260
5. Liquid treatment and solid handling equipment, including pumps	66,130	105,740
6. Piping and ducting (2)	159,370	135,580
7. Instrumentation and electrical material (3)	30,270	20,670
TOTAL EQUIPMENT COST -	487,050	413,410
B. Annual Operating Costs		
1. Electrical power for fans and pumps	159,170	60,370
2. Annualized capital charges and depreciation (20% of capital costs)	97,410	82,680
TOTAL	$256,580	$143,050

Notes:

1. Actual costs obtained from the user, converted to 1978.
2. Due to equivalent complexity, the costs were assumed same for both systems.
3. Taken as 5% of equipment costs for the F/C system.
4. Quench spray costs for both the systems are included in the ducting costs.

TABLE 3. COST COMPARISON FOR PREMIUM WIRE RECOVERY

COST ITEM	COST FOR F/C	COST FOR CONVENTIONAL
Venturi	$ 1,700	$ 1,700
Cooling Tower	8,900	0
Condenser	4,040	4,040
Saturator	5,060	5,060
Blower & Motor	3,790	14,450
Total Equipment	23,490	25,340
Total Capital Investment	$103,121	$111,242
Depreciation	$10,310	$ 11,125
Maintenance	6,185	6,675
Water	180	180
Raw Materials	1,650	1,650
Power	2,370	11,530
Total Annual Cost	$20,695	$31,160

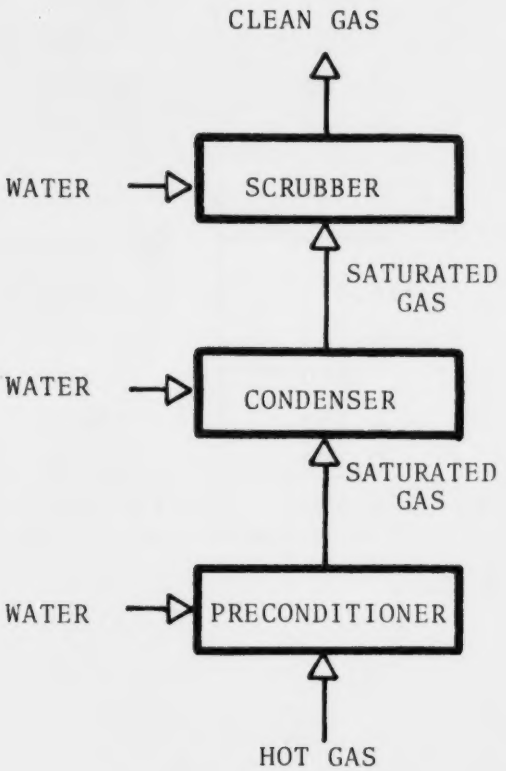

Figure 1. Simplified F/C scrubber system.

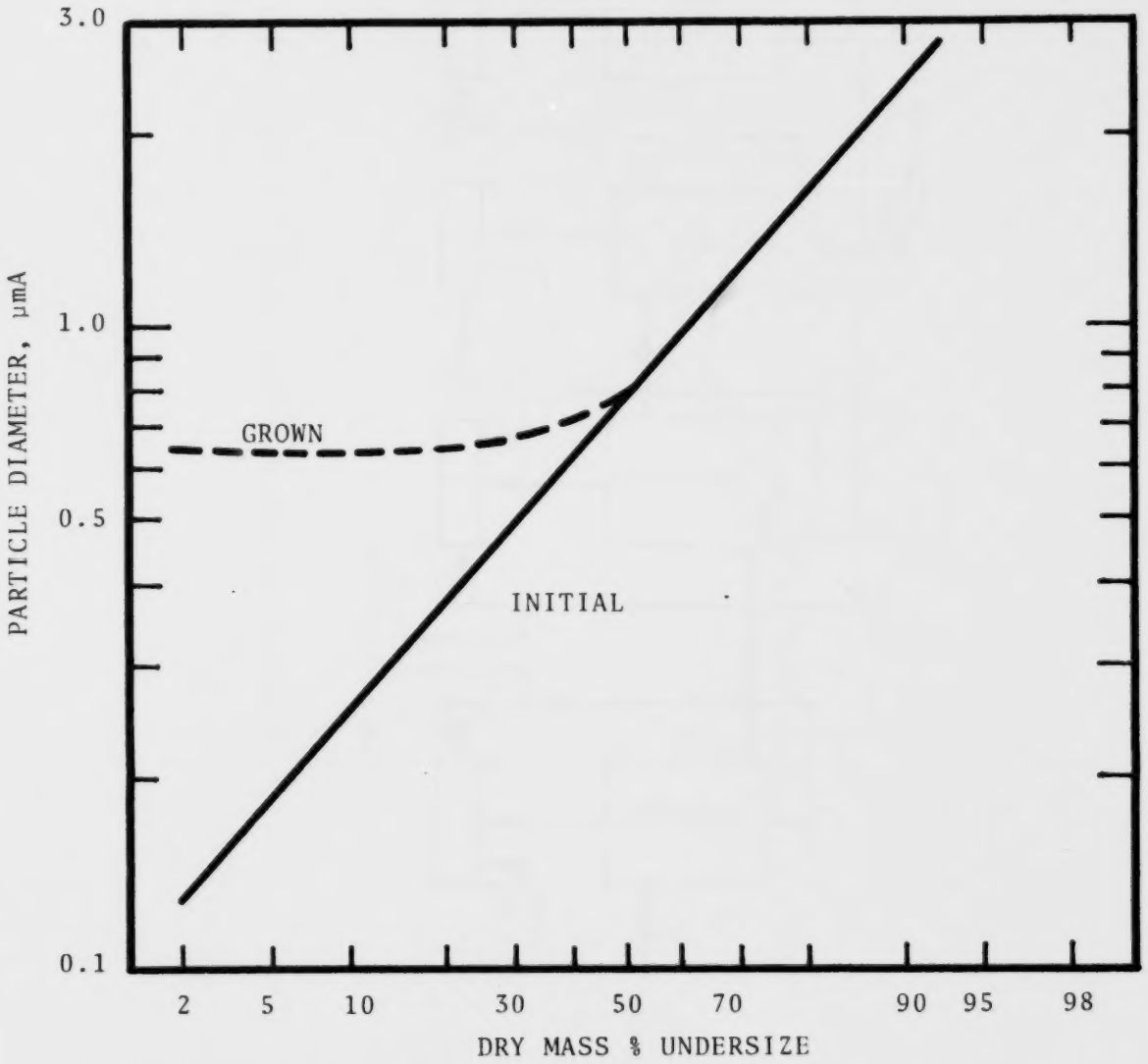

Figure 2. Particle size distribution before and after condensation for 10^9 particles/DNcm^3.

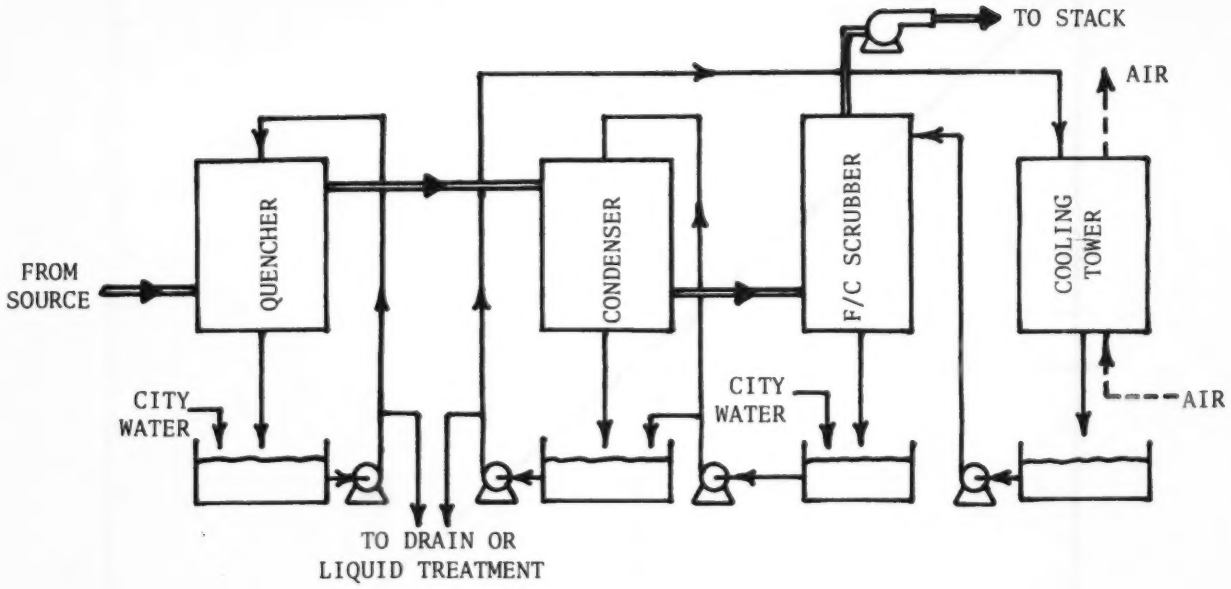

Figure 3. Generalized process design for F/C scrubber system.

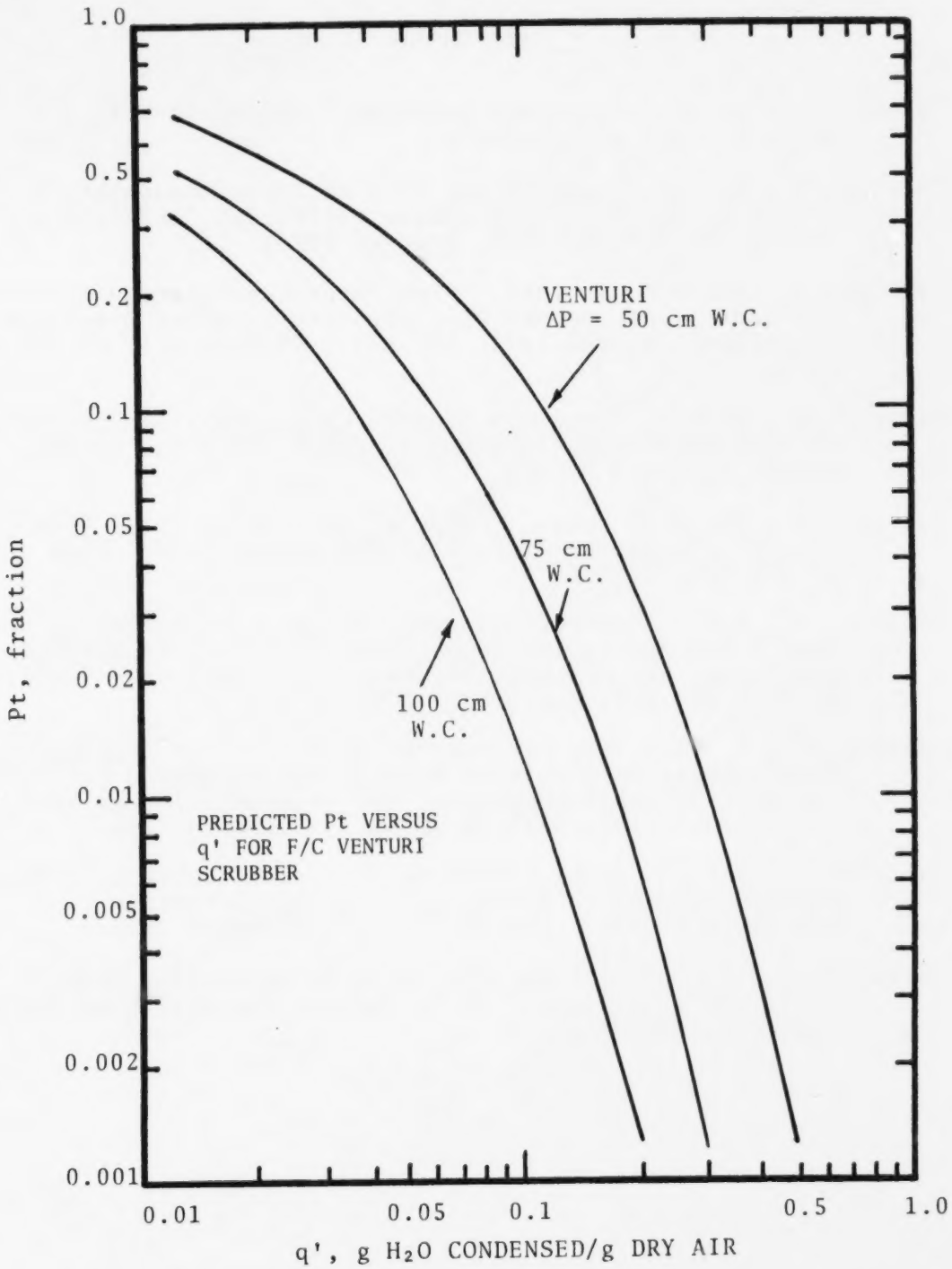

Figure 4. Predicted performance for F/C venturi scrubber. Initial particle diameter=0, n_p=10^8 particles/cm^3, 20% condensate on particles, ρ_G = 0.0011 g/cm^3, ρ_p = 1.0 g/cm^3.

BIBLIOGRAPHY

Calvert, S., et al., "Scrubber Handbook," EPA-R2-72-118a, NTIS PB 213-016, July 1972.

Calvert, S., et al., "Feasibility of Flux Force/Condensation Scrubbing for Fine Particulate Collection," EPA-650/2-73-036, NTIS PB 227-307, October 1973.

Calvert, S., and N.C. Jhaveri, "Flux Force/Condensation Scrubbing," Proceedings of the EPA Fine Particle Scrubber Symposium, San Diego, CA, May 1974, EPA-650/2-74-112, NTIS PB 239-335, 1974.

Calvert, S., et al., "Study of Flux Force/Condensation Scrubbing of Fine Particles," EPA-600/2-75-018, NTIS PB 249-297, August 1975.

Calvert, S., and S.C. Yung., "Study of Horizontal Spray Flux Force/Condensation Scrubber," EPA-600/2-76-200, NTIS PB 262-669, July 1976.

Calvert, S., and S. Gandhi, "Improved Design Method for F/C Scrubbing," Proceedings of Second EPA Fine Particle Scrubber Symposium, New Orleans, LA, May 1977, EPA-600/2-77-193, NTIS PB 272-828, September 1977.

Calvert, S., et al., "F/C Scrubber Demonstration on a Secondary Metals Recovery Furnace," Proceedings of Second EPA Fine Particle Scrubber Symposium, New Orleans, LA, May 1977, EPA-600/2-77-193, NTIS PB 273-828, September 1977.

Calvert, S., and S. Gandhi, "Fine Particle Collection by a Flux Force/Condensation Scrubber: Pilot Demonstration," EPA-600/2-77-238, NTIS PB 277-075, December 1977.

Whitmore, P.J., "Diffusiophoretic Particle Collection Under Turbulent Conditions," Ph.D. Thesis, University of British Columbia, Canada, 1976.